UPGRADE OF THE VTI T-38 BLOWDOWN TRISONIC TEST FACILITY: WIND TUNNEL CONTROL SYSTEM

Biljana Ilić[1], Goran Ocokoljić[2], Marija Samardžić[3] & Jovan Isaković[4]

[1]Military Technical Institute (VTI), Belgrade, Serbia
[2]Military Technical Institute (VTI), Belgrade, Serbia
[3]Military Technical Institute (VTI), Belgrade, Serbia
[4]Academy of Applied Technical Studies, Belgrade, Serbia

Abstract

The paper addresses a recent major facility upgrade of the VTI T-38 wind tunnel. More than 30 years after the wind tunnel commissioning, a novel solution for test automation developed by VTI brings more than an order of magnitude improved testing accuracy, higher versatility of information obtained from the tests, as well as significantly reduced wind-on time and energy consumption, confirming the VTI T-38 ability to perform tests with uniform quality from low subsonic speeds via transonic conditions and up to high supersonic speeds.

Keywords: wind tunnel, aerodynamic experiment, control system, nonlinearity, feedforward.

1. Introduction

Blowdown trisonic wind tunnels present a cost-effective experimental tool to duplicate actual flight conditions in three speed regimes – subsonic, transonic, and supersonic. However, significant physical differences existing between subsonic and supersonic flows bring difficulties in design, control and operation of such facilities. The potential effect of wind tunnel on measured characteristics of models of aerospace vehicles is different in different speed regimes. Complexities associated with solid and wake blockage [1], wall interference properties [2], boundary layer growth [3], pressure gradient in the test section, unsteady flow resulting in shock wave and boundary layer interactions [4], reflection of shock waves or expansion waves from the walls [5] etc., are more or less emphasized in different regions of a broad operating envelope of a blowdown trisonic facility.

With the main goal being to eliminate the wind tunnel as a parameter for measured data accuracy, an array of control techniques is applied in an effort to maintain an adequate flow with uniform quality from subsonic speeds via transonic conditions and up to supersonic speeds. These techniques need to be applied within an automation platform that maximizes performance and productivity, both equally important in the era of fast technological changes [6]. However, in addition to facility management functions offered by typical automation solutions for industrial plants, a key challenge in wind tunnel control design is brought by the test management functions, with a completely different set of requirements (Figure 1). Thus, in order to achieve scalability, modularity and flexibility, any modern wind tunnel automation platform has to offer both true separation of facility and test functions, and their complete integration.

In the VTI T-38 wind tunnel [7], an automation platform bringing a number of upgrades of facility control and operation, as well as testing technologies and methods has been introduced in recent years to adapt to ever more stringent and versatile customer requirements. The results achieved are reflected not only in more than an order of magnitude improved testing accuracy, but also in the versatility of information obtained from the tests, as well as significantly reduced wind-on time and energy consumption to achieve the same technical objective [8].

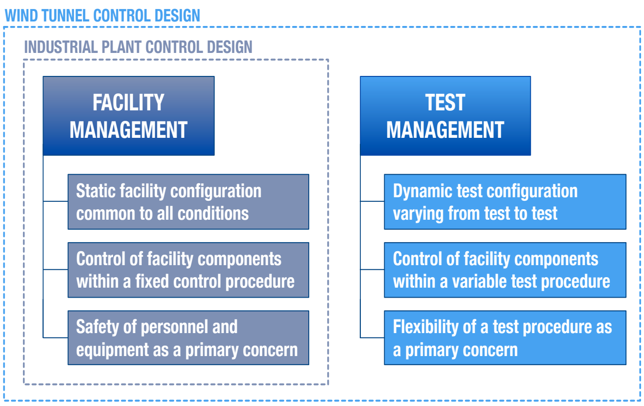

Figure 1 – Test and facility functions in wind tunnel control design.

This paper specifically addresses the VTI T-38 wind tunnel control system as a recent major facility upgrade and an essential part of the developed automation platform.

2. Overview of the VTI T-38 wind tunnel automation platform

A novel solution developed by VTI for automation of aerodynamic experiments in the VTI T-38 test facility (Figure 2) recently replaced the original system delivered during the wind tunnel commissioning, more than 30 years ago [9]. Unlike the former system, which was designed specifically for the VTI T-38 wind tunnel [10], the current solution also represents an automation framework for any blowdown test facility, with horizontal architecture that can be scaled depending on both the complexity of the facility and the required test type.

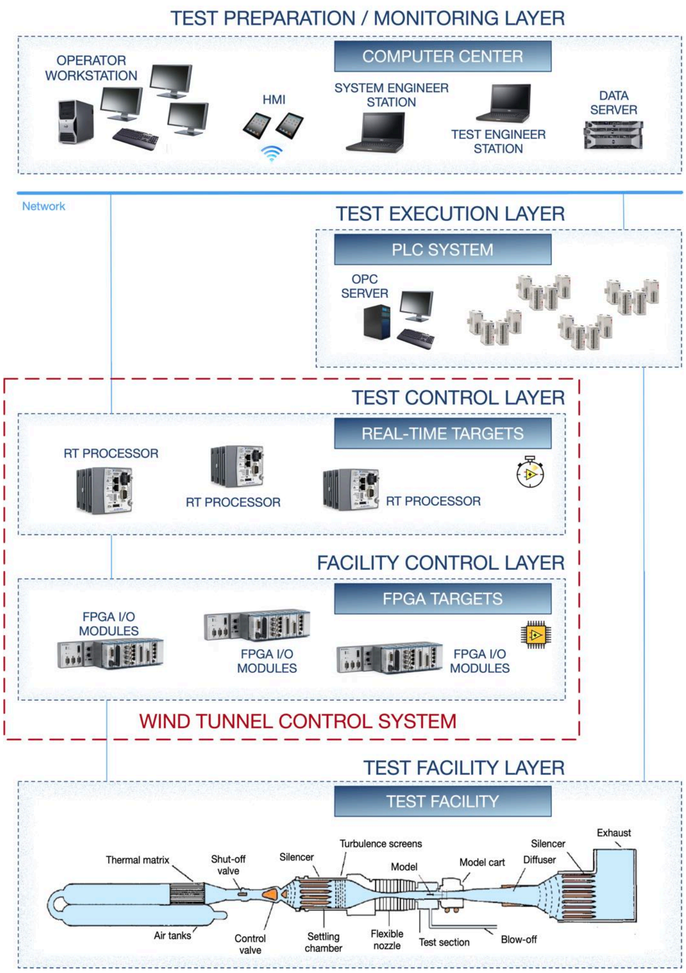

Figure 2 – VTI T-38 wind tunnel automation platform.

The VTI T-38 wind tunnel automation platform delivers vertical integration of facility and test functions in a five-layer hierarchical architecture. Different levels of abstractions of the test facility are used at each level of the hierarchy.

2.1 Test Facility Layer

The test facility layer comprises the actual wind tunnel, with all its components representing more or less complex motion systems. The VTI T-38 test facility (Figure 3) is a large-scale blowdown wind tunnel designed to fulfil testing requirements in the Mach number range of 0.2 – 4.0, with the Reynolds number capability of 100 MRe per meter. The high Reynolds number requirements are satisfied by raising air density, with controllable range of blowing pressures between 0.12 MPa and 1.5 MPa. The test section size is 1.5 m $\times$ 1.5 m, with a 2 DOF model support system that permits movement of the model within ±20° in pitch and ±720° in roll [11] [12].

Figure 3 – VTI T-38 blowdown trisonic test facility.

The flow is established by the discharge of the 2600 m^3 tanks, pressurized to up to 2 MPa, to the atmosphere, with available run time from 6 to 60 seconds, depending on required flow conditions. A solid-wall test section is used for subsonic and supersonic tests, while a porous-wall test section with variable porosity and an ejector-assisted blow-off system is inserted in the wind tunnel circuit for transonic tests.

The VTI T-38 test facility consists of sixteen major motion systems that are expected to work both independently and, during a wind tunnel test, in tight synchronization with each other to achieve the desired flow around a model in the test section.

2.2 Facility Control Layer

Facility Control Layer consists of a set of low-level control laws for motion control of the VTI T-38 wind tunnel systems. Each of these systems is interfaced with the facility control layer via position sensors and actuators. In total, 34 high-resolution digital position sensors are used as position feedback, while 52 hydraulic, pneumatic and electric actuators are used to accomplish physical movement of different components.

Within the VTI T-38 wind tunnel automation platform, this layer resides on the user-programmable FPGA targets, where parallel nature of the FPGA enables simultaneous execution of low-level control loops for different motion subsystems, such as the control valve, variable-geometry nozzle, model support, second throat, blow-off system, etc. In addition, it allows Facility Control Layer to be easily scaled if additional subsystems are to be introduced for non-standard test types.

As an example, the VTI T-38 variable-geometry nozzle is one of sixteen wind tunnel major components, with 19 jack station supporting upper and lower 1.5 m × 11 m flexible plates lengthwise, between two parallel fixed walls (Figure 4). It represents a multi-sensor multi-actuator system within Test Facility Layer, which is interfaced with Facility Control Layer via 19 high-power and 19 low-power electric motors driving 76 screw stops, 19 position sensors used as position feedback, pressure and temperature sensors used as a feedback for the hydraulic system and 144 over-curvature sensors as interlocks with the nozzle positioning procedure.

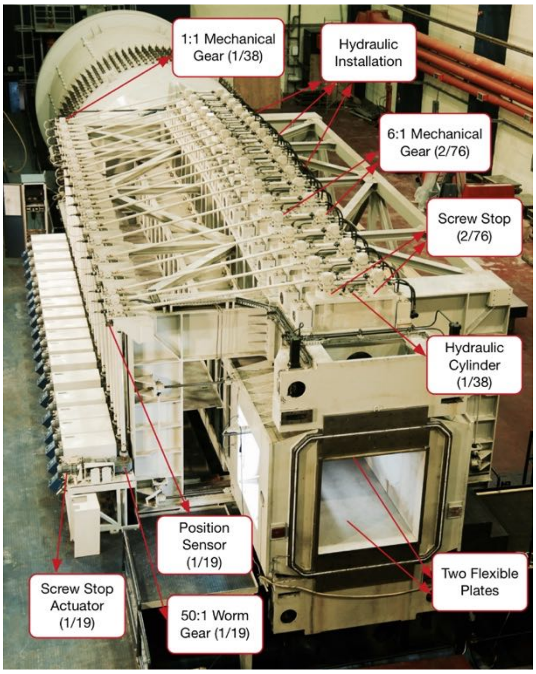

Figure 4 – VTI T-38 wind tunnel variable geometry-nozzle.

Using the FPGA targets and a parallel computing approach, and replacing resolvers and the resolver-to-digital unit used in the former control system implementation by high-resolution multiturn encoders, the speed of operation is improved for several orders of magnitude, with the control cycle for all 19 jack stations of 0.2 ms versus 1140 ms in the previous implementation. Almost 6000 times faster control cycle now enables fully automatic nozzle positioning with an accuracy of 0.01 mm compared to the former semi-automatic procedure with a positioning accuracy of 0.03 mm [13] [14].

2.3 Test Control Layer

Test Control Layer consists of a set of high-level control algorithms for the control of test conditions, such as blowing pressure, Mach number or model movement. The desired test conditions are achieved by one or several facility components working in synchronization. Thus, blowing pressure is actively controlled by the movement of the control valve in all three speed ranges of the facility. In subsonic and supersonic ranges, Mach number is controlled by setting the second throat and the nozzle contour, respectively, while in the transonic range, a system consisting of blow-off valves with ejector assist is used in addition. The desired model movement profile is generated by combining pitch and roll motion subsystems.

Test Control Layer within the VTI T-38 automation platform is implemented on the embedded controllers with real-time processors. The embedded software executes high-level control loops for the control of test conditions and synchronously records the test data, both for real-time monitoring and further offline analysis. This layer can be scaled by adding control laws for additional test types.

2.4 Test Execution Layer

Test Execution Layer is primarily concerned with maintaining safe conditions of operation of a high-pressure facility, such as the VTI T-38 wind tunnel. It is directly interfaced with Test Facility Layer via a number of sensors whose status determines the sequence of operations needed to safely execute a particular test type.

In the VTI T-38 wind tunnel, this layer is based on an independent programable logical controller (PLC) with five remote units, interfaced with the facility via more than 700 physical inputs/outputs and programmed using more than 300 logical variables. Test Execution Layer can be easily scaled for additional systems and test types, since the automation platform supports any available PLC hardware, by using open OPC interface standard for communication with hardware devices.

2.5 Test Preparation/Monitoring Layer

This layer consists of a set of test preparation/monitoring procedures corresponding to different test types. It enables users to choose from standard test types or define new test types.

Test Preparation/Monitoring Layer can reside on one or more commercially available personal computers. The software features graphical user interfaces (GUI) for different users and purposes, such as operator workstation GUI, system engineer diagnostics GUI or test engineer experiment monitoring GUI. A data server delivers database services.

3. Wind tunnel control system

The VTI T-38 wind tunnel control system is an essential part of the developed automation solution. The primary task of the wind tunnel control system is high-level control of the flow relying on low level control of the corresponding facility components. Taking into account this functional hierarchy, the facility and test functions included in the VTI T-38 wind tunnel control system are separated and placed within Facility Control Layer and Test Control Layer, respectively, which represents the unique feature of this concept (Figure 2). The integration of separated facility and test functions is demonstrated here using the case of blowing pressure as the primary parameter characterizing the mean flow field in a blowdown wind tunnel.

Different configurations of a trisonic blowdown wind tunnel are used for different speed ranges, but its operation is based on the common aerodynamic principles. Flow is established due to a pressure difference between high pressure chamber at the entrance of the facility and atmosphere at the exit. At the end of a supersonic nozzle sits the test section, with the supersonic Mach number uniquely determined by the area ratio between the test section and the nozzle throat [15]. The same principle is applied in subsonic range, but instead of the nozzle, the second throat at the end of the test section is used to create throat conditions and generate subsonic flow in the test section. Subsonic Mach number is then uniquely determined by the area ratio between the test section and the second throat. An additional test section with porous walls and blow-off system is used for transonic speeds. In all cases, the required Reynolds number of a scaled wind tunnel model is regulated by providing corresponding high blowing pressure.

A simplified supersonic configuration of the VTI T-38 wind tunnel is shown in Figure 5, with five designated facility components important for blowing pressure control. In blowdown wind tunnel design, stagnation flow conditions are assumed to be achieved in the plenum, so that pressure measured in the plenum represents stagnation pressure or blowing pressure.

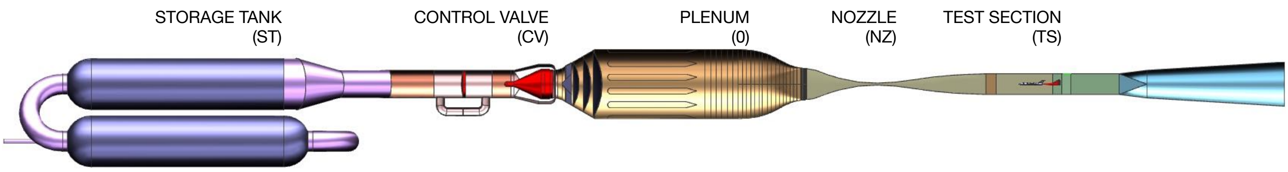

Figure 5 – Supersonic configuration of the VTI T-38 wind tunnel.

3.1 Control objectives

Constant blowing pressure during a test is one of the basic and most common requirements in wind tunnel testing. The desired blowing pressure is first achieved and then maintained as the tank pressure decreases for the duration of a test.

The facility component used to achieve the blowing pressure control objectives in the VTI T-38 wind tunnel is the custom-designed sleeve valve (Figure 6), with a central part that can move along the wind tunnel axis, thus changing air flow from the tank (Figure 5). The moving part is actuated by a hydraulic actuator, consisting of a servo valve and a hydraulic cylinder, with valve linear displacement measured as a position feedback.

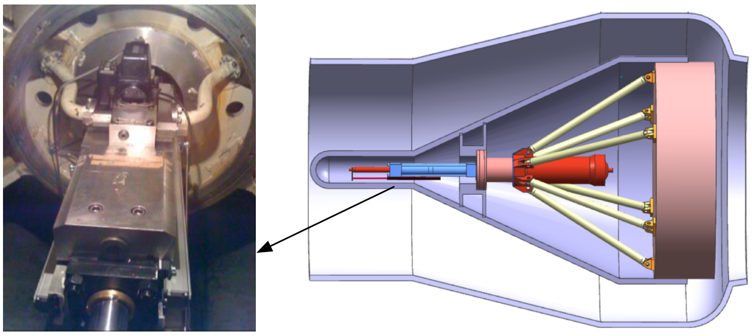

Figure 6 – Control valve in the VTI T-38 wind tunnel.

The VTI T-38 facility parameters relevant for blowing pressure control are the following:

Storage tank volume:	2600 m^3
Storage tank maximum pressure:	2 MPa
Plenum volume:	360 m^3
Plenum maximum pressure:	1.5 MPa
Control valve maximum flow area:	1.8 m^2
Control valve maximum stroke length:	0.5 m
Test section flow area:	2.25 m^2
Maximum ratio of test section and throat flow areas:	10.8
Maximum ratio of valve and throat flow areas:	8.6

The blowing pressure control is divided into three phases, and the ideal pressure change is shown in Figure 7. In the first phase, the desired supersonic flow is established, with systems of strong shock waves passing through the test section and subjecting the tested model to high aerodynamic loads. This phase should be kept short, both to reduce loads and improve efficiency by saving test time. In the second phase, which represents the available test time, blowing pressure is maintained as close as possible to the desired value. Flow is stopped in the third phase.

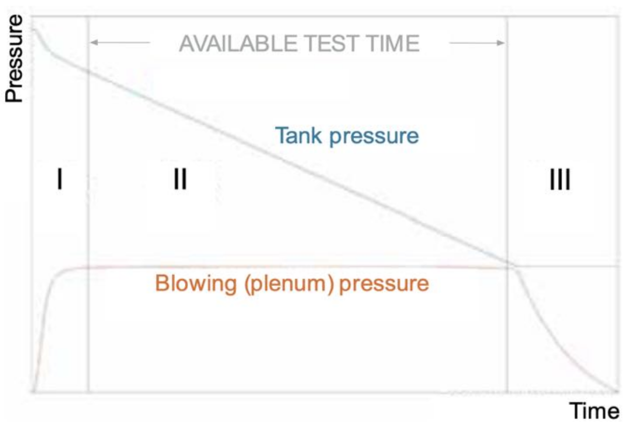

Figure 7 – The blowing pressure control objectives.

The stated control objectives must be met over a wide range of testing conditions, with nonlinearities present both in a single operating point, and over an operating range of the test facility. Some of the challenges that have to be overcome are nonlinear flow and valve dynamics, different flow and valve time constants, a variable ratio of the time constants in the operating range, variable flow conditions upstream the valve, uncertainty in predicting the valve flow characteristics etc.

Two approaches are commonly taken to dealing with these problems. One is to use an array of linear controllers optimized around specific operating points, and the other approach involves using nonlinear controllers. In both cases, the complexity of compressible flow dynamics combined with uncertainties due to control element dynamics leads to a complicated controller adjusting procedure and a range of different control terms for different operating conditions.

Using linear controllers in discrete operating points for a highly nonlinear process is a safe and always feasible approach, but it leads to a multitude of control terms, usually obtained after several tuning attempts for each point [16]. In addition, nonlinearity at the operating point prevents obtaining a good accuracy [17]. On the other hand, complex nonlinear controllers with complicated adjusting procedures are impractical from considerations of economy and reliability of wind tunnel operations [18] [19].

In contrast, the approach adopted in the VTI T-38 wind tunnel is based on two ideas:

- Identifying and compensating the main nonlinearities by modelling compressible flow dynamics.
- Separating test and facility functions within the automation platform presented in Figure 2, ie. decoupling between flow dynamics at Test Control Layer and control valve dynamics at Facility Control Layer, by analyzing the process' physical properties and identifying distinct contributions to the overall process gain, originating from flow dynamics and valve dynamics.

3.2 Modelling flow dynamics

A lumped parameter approach [20] is applied to modeling flow dynamics. Five control volumes are selected: the storage tank, the control valve, the plenum, the nozzle and the test section (Figure 5). It is assumed that all processes are isentropic and that air behaves as a perfect gas.

The conservation of mass and energy equations applied to the storage tank and the plenum become, respectively [21]:

$$\frac{d\rho_{ST}}{dt} = -\frac{1}{V_{ST}}\dot{m}_{CV} \tag{1}$$

$$\frac{dP_{ST}}{dt} = -\frac{\kappa R}{V_{ST}}T_{ST}\dot{m}_{CV} \tag{2}$$

$$\frac{d\rho_0}{dt} = -\frac{1}{V_0}(\dot{m}_{CV} - \dot{m}_{NZ}) \tag{3}$$

$$\frac{dP_0}{dt} = \frac{\kappa R}{V_0}(T_{ST}\dot{m}_{CV} - T_0\dot{m}_{NZ}) \tag{4}$$

where ρ is density, P pressure, T temperature, V volume, κ the ratio of air specific heats, R the air gas constant, and $\dot{m}$ is mass flow. Indexes *ST*, *CV*, *0* and *NZ* denote the storage tank, the control valve, the plenum and the nozzle, respectively.

Mass flow through the control valve is calculated for both choked and unchoked flow:

$$\dot{m}_{CV} = \sqrt{\frac{2\kappa}{R(\kappa-1)}}\frac{P_{ST}}{\sqrt{T_{ST}}}A_{CV}\left(\frac{P_{CV}}{P_{ST}}\right)\sqrt{1-\left(\frac{P_{CV}}{P_{ST}}\right)^{\frac{\kappa-1}{\kappa}}} \tag{5}$$

where A represents cross-section area. Equation (5) is valid for unchoked flow with $P_{CV} / P_{ST} \geq 0.5283$. For $P_{CV} / P_{ST} < 0.5283$, the flow through the control valve is choked and mass flow is calculated for $P_{CV} / P_{ST} = 0.5283$ [15].

Nozzle mass flow is calculated assuming choked flow, which is a necessary condition for a supersonic Mach number to be achieved in the test section:

$$\dot{m}_{NZ} = \sqrt{\frac{\kappa}{R}\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{2(\kappa-1)}}}\frac{P_0}{\sqrt{T_0}}A_{NZ} \tag{6}$$

In order to numerically solve the system (1) – (6), temperature is expressed as a function of pressure and density using the perfect gas relation [15]:

$$P_{ST} = \rho_{ST}RT_{ST}\ ;\ P_0 = \rho_0 RT_0 \tag{7}$$

The nozzle throat area in the supersonic flow is [10]:

$$A_{NZ} = A_{TS} M_{TS} \left(\frac{5+M_{TS}^2}{6}\right)^{-3} \tag{8}$$

A key challenge in using this model is the uncertainty in the valve flow characteristics, caused by the fact that reliable measurement of the valve outlet static pressure, P_{CV}, is not feasible. Consequently, this pressure must be estimated. The models available in literature [16] [22] [23] [24] mostly assume that the valve outlet pressure (P_{CV}) is equal to the plenum pressure (P_0). That way, valve exit flow is treated as a jet expanding into an infinite volume, and the total pressure loss as equal to the jet dynamic pressure. Conversely, explicit loss estimates for the individual plenum components indicate that the pressure loss is in fact higher than the dynamic pressure [25]. To avoid considering component losses separately, the total loss from the valve to the plenum exit is here expressed as:

$$P_{ST} - P_0 = K(P_{ST} - P_{CV}) \tag{9}$$

where $K \geq 1$ is the plenum pressure loss coefficient.

Thus, a dynamic model of the flow in a supersonic blowdown facility consists of four first-order nonlinear ordinary differential equations (1) – (4) and five algebraic equations (5) – (9). The model has four state variables: ρ_{ST}, P_{ST}, ρ_0 and P_0. The inputs to the model are the control valve cross-section area (A_{CV}) and Mach number (M_{TS}). The output of the model is the blowing pressure (P_0).

The flow dynamics model presented here is applicable to any supersonic blowdown test facility. The valve is represented only by its cross-section area, A_{CV}, without taking into consideration its internal dynamics. By capturing only flow dynamics that is common to all facilities, the model can be used to analyze the response of any blowdown wind tunnel and identify nonlinearities originating from flow dynamics separately from valve nonlinearities.

3.3 Typical control strategy

The blowdown wind tunnel practice abounds with linear single-loop control solutions, with proportional-integral-differential (PID) controller as the most adopted control strategy. A typical PID implementation of the blowing pressure control is shown in Figure 8.

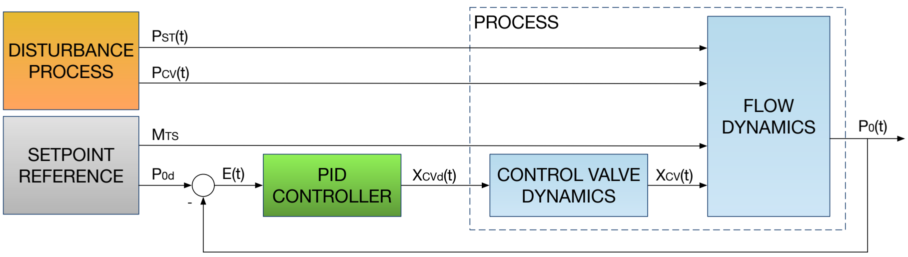

Figure 8 – Typical PID-based blowing pressure control.

The single-loop controller adjusts valve position (X_{CV}) based on an error value (E), calculated as a difference between a setpoint (P_{0d}) and a measured pressure (P_0). However, in addition to the valve position, P_0 is also a function of P_{ST} and P_{CV}, which represent the main disturbances in an operating point, and M_{TS}, which is a main source of nonlinearity between operating points. Consequently, this approach requires significant tuning efforts for different operating points. In addition, a PID controller with a single set of control terms per operating point results in poor blowing pressure accuracies, in range of ±1-2% [16] [17] [22]

The main issue with this type of implementation is that the control system, by directly adjusting valve position, tries to counteract both flow dynamics and valve dynamics, which are combined within a single process notwithstanding different time constants and sources of nonlinearities. In order to better identify and compensate nonlinearities, as well as to achieve better control accuracy, decoupling between flow and valve dynamics is needed.

3.4 Decoupling flow and valve dynamics

The gain of the process shown in Figure 8 represents the rate of change of blowing pressure (P_0) with the desired valve position (X_{CVd}) and can be expressed as:

$$\frac{dP_0}{dX_{CVd}} = \frac{dP_0}{dA_{CV}}\frac{dA_{CV}}{dX_{CV}}\frac{dX_{CV}}{dX_{CVd}} \tag{10}$$

where X_{CV} is the measured valve position. According to the model (1) – (9), the first term (dP_0/dA_{CV}) represents the contribution of flow dynamics to the overall process gain. The rate of change of valve flow area with valve position (dA_{CV}/dX_{CV}) describes the contribution of valve geometry. Finally, the valve dynamic response (dX_{CV}/ dX_{CVd}) provided by its actuator and sensor represents the contribution of the valve internal dynamics.

By identifying distinct contributions of the flow dynamics and valve dynamics to the process gain (10), two main issues present in the PID implementation (Figure 8) can be resolved. First, to achieve high performance setpoint response, a control strategy must be designed taking into account flow time constants that are typically several times longer than the valve time constants. In addition, the ratio of these time constants varies in the operating range due to high mass flow rate differences. In the VTI T-38 facility, mass flows vary from around 300 kg/s to 3500 kg/s depending on the blowing pressure and Mach number variation. Second, to achieve high performance disturbance rejection, a control strategy must be designed to compensate flow nonlinearities more efficiently due to slower flow dynamics.

3.5 Control strategy in the VTI T-38 wind tunnel

The control strategy adopted in the VTI T-38 wind tunnel is based on the process physical properties presented in analysis of the process gain (10). First, decoupling between slower flow dynamics and faster valve dynamics in a cascade control architecture is proposed. Flow and valve nonlinearities then can be managed in separate loops within a double-loop scheme. Second, feedforward with feedback trim architecture is suggested. Feedforward action is intended to address process nonlinearities, while remaining disturbances are counteracted by feedback action. If the feedforward action successfully eliminates most of the process nonlinearities, a single set of feedback control terms could be used in an entire operating range. Therefore, this approach is expected to significantly reduce tuning efforts, despite the double-loop scheme. The blowing pressure controller that combines the two control architectures is shown in Figure 9.

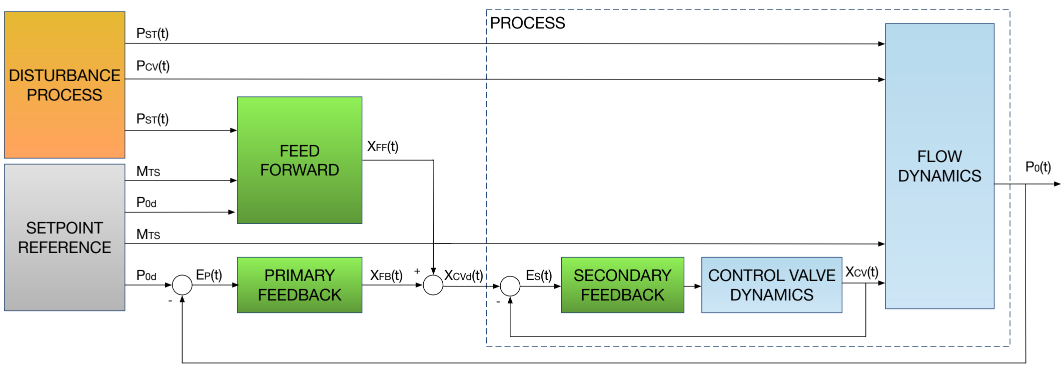

Figure 9 – The blowing pressure control strategy in the VTI T-38 wind tunnel.

Valve dynamics is managed in the secondary loop, and flow dynamics in the primary loop. The primary and secondary measured process variables are blowing pressure (P_0) and valve position (X_{CV}), respectively.

In the primary loop, feedforward uses tank pressure (P_{ST}) and estimated plenum loss (K) to compute preemptive valve position (X_{FF}) that counteracts the predicted disturbance impact for current nozzle configuration (M_{TS}). Feedback action trims out additional deviations from blowing pressure setpoint

(P_{0d}) and improves setpoint tracking. The sum of feedforward (X_{FF}) and feedback (X_{FB}) outputs represents the setpoint valve position (X_{CVd}) for the secondary loop. The secondary process objective is to achieve valve flow position (X_{CV}) corresponding to the setpoint (X_{CVd}) as fast as possible. The secondary controller thus manipulates the internal valve control, sending a command signal to the valve actuator based on X_{CVd} and a measured valve position X_{CV}.

3.6 Nonlinearity compensation

The feedforward action in the adopted blowing pressure controller eliminates nonlinearities originating from flow dynamics and valve geometry (10). To maintain a constant blowing pressure during a test it is necessary to maintain constant conditions downstream the valve despite the tank pressure drop. It is possible only if flow is stabilized around the desired conditions, i.e., if the valve mass flow (5) matches the flow through the nozzle throat (6). If temperature drop due to expansion is neglected, the feedforward valve area (A_{FF}) is obtained by equalizing (5) and (6):

$$\frac{A_{FF}}{A_{NZ}} = \sqrt{\frac{\kappa-1}{2}}\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{2(\kappa-1)}}\frac{P_{0d}}{P_{ST}}\left(\frac{P_{CVd}}{P_{ST}}\right)^{-\frac{1}{\kappa}}\left(1-\frac{P_{CVd}}{P_{ST}}\right)^{\frac{\kappa-1}{\kappa}} \tag{11}$$

where P_{CVd} (P_{0d}, K) is the desired valve outlet static pressure defined by (9). Note that equation (11) is valid for $P_{CV}/P_{ST} \geq 0.5283$. Otherwise, mass flow is calculated for $P_{CV}/P_{ST} = 0.5283$. Also note that, according to (8), a nozzle throat area (A_{NZ}) uniquely determines Mach number (M_{TS}). Thus, M_{TS} and P_{0d} are desired conditions defined at the beginning of a wind tunnel test, P_{ST} is the measured disturbance, and K is the estimated plenum loss.

In an operating point, tank pressure (P_{ST}) and plenum loss (K) are the most prominent sources of nonlinearity. Their effect to the feedforward valve area (A_{FF}) needed to maintain flow with the desired blowing pressure (P_{0d}) at the desired Mach number (A_{NZ}) is presented in Figure 10. The curve K = 1.35 applies to the VTI T-38 wind tunnel. By using an appropriate loss estimation, similar relationship can be obtained for any facility. The nonlinearity level noticeably increases as the P_{0d}/P_{ST} ratio increases towards the end of a test.

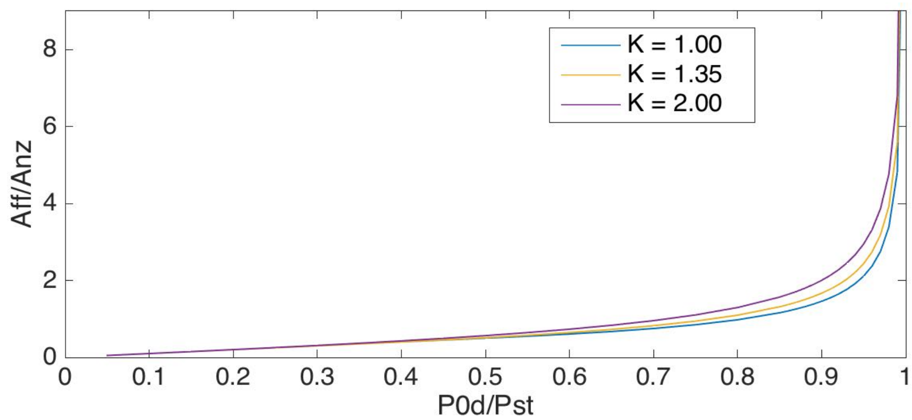

Figure 10 – Effect of tank pressure and plenum loss in an operating point to the feedforward valve area

In Figure 11, the effect of Mach number is added to tank pressure effect for the VTI T-38 wind tunnel, to demonstrate the influence of flow dynamics nonlinearities in the facility operating range. Finally, the effect of the valve geometry is added in Figure 12. The geometrical position-area relationship for the valve used in the VTI T-38 facility is represented by the sixth-order polynomial [21].

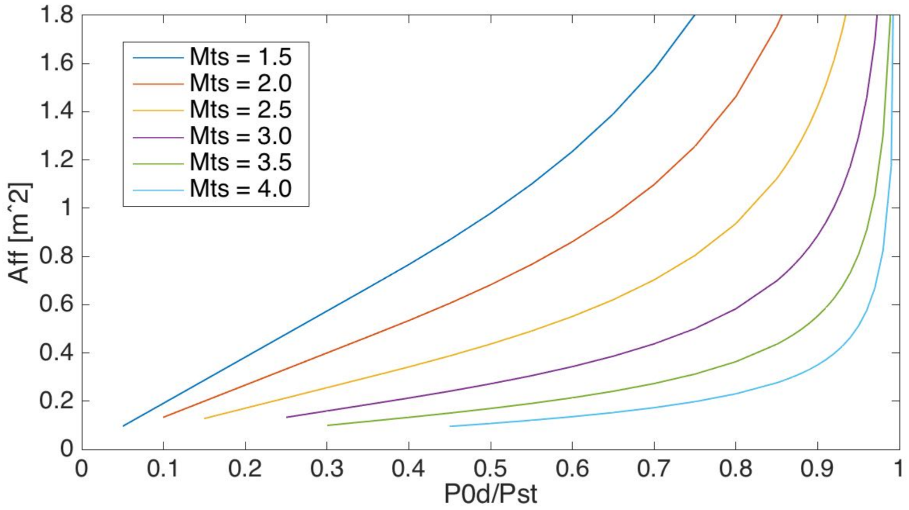

Figure 11 – Effect of flow dynamics to the feedforward valve area
in the VTI T-38 test facility

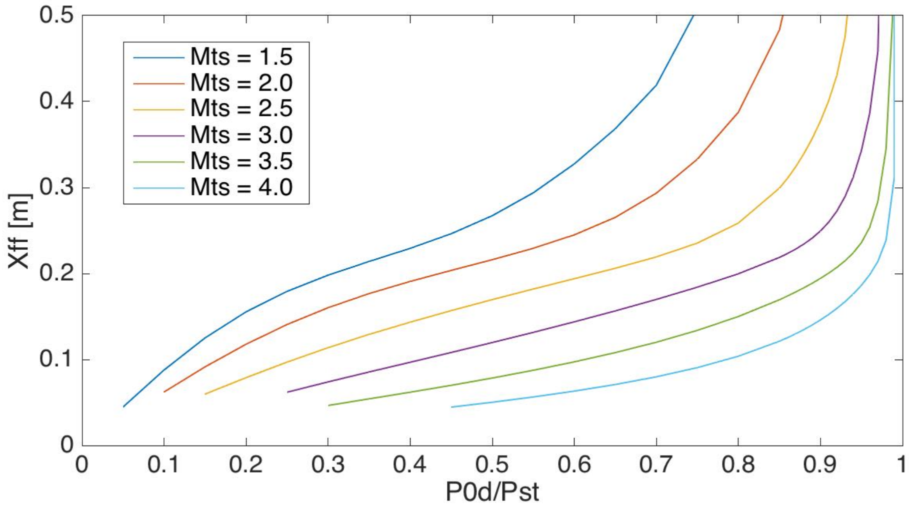

Figure 12 – Effect of flow dynamics and valve geometry to the feedforward valve position
in the VTI T-38 test facility

Comparing Figure 11 and Figure 12, it can be noticed that the valve geometry diminishes the effect of Mach number, i.e., the effect of nozzle configuration, at lower supersonic speeds. Thus, the valve is designed to reduce nonlinearities in the operating range of the facility.

In addition, Figure 11 shows a significant difference between lower and higher supersonic speeds. Higher speeds correspond to smaller mass flow rates, and consequently, smaller valve areas are needed to sustain the desired flow. The required valve area rapidly increases when there is insufficient tank pressure. The effect of tank pressure is obviously dominant to the Mach number effect. On the contrary, larger valve areas are needed to sustain the desired flow at lower speeds. Maximum valve area is reached when tank pressure is still significantly higher than desired blowing pressure. Thus, the Mach number effect is more prominent than the effect of tank pressure.

3.7 Control strategy implementation

The adopted strategy for blowing pressure control is implemented in the VTI T-38 test facility. The feedback control terms are tuned in numerical simulations using the models of the process and the controller. The controller designed in Simulink is given in Figure 13. Flow dynamics block (FDM) is a function that solves the model (1) – (9) using the fixed time-step finite difference technique. Feedforward block (FF) is based on (11), and its input is tank pressure obtained in each time step by solving FDM. Both primary and secondary loops are closed using a PI controller.

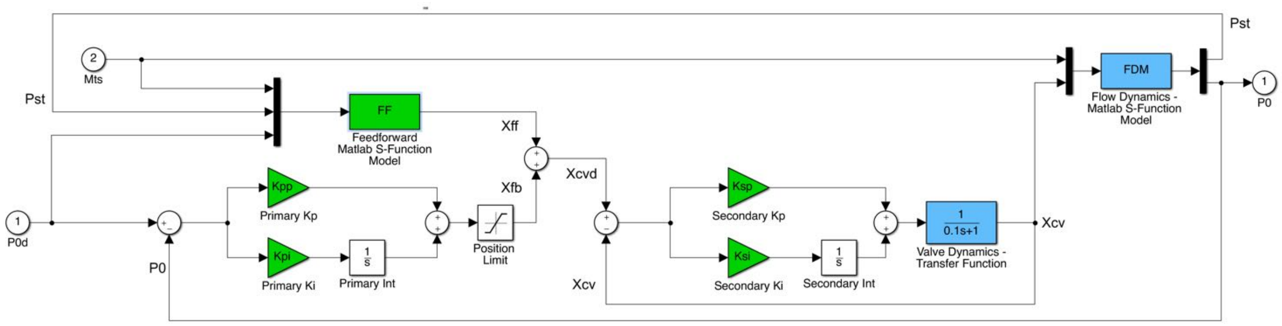

Figure 13 – Simulink model of the blowing pressure controller

The secondary feedback control terms (Ksp, Ksi) are tuned via simulation and experiment. Once implemented, the secondary controller effectively becomes a part of the process. Its control terms are therefore fixed and accepted, and then the primary feedback control terms (Kpp, Kpi) are tuned. Simulations are run for the entire operating range, with the objective to achieve both good setpoint tracking and disturbance rejection. The implicit objective was to find a single set of Kpp and Kpi applicable to all operating conditions and thus validate predictions by the steady-state nonlinearity compensation algorithm. Based on numerical simulations, the values selected for the feedback control terms are the following:

Ksp:	2.8	Kpp:	$5.4\ m \cdot MPa^{-1}$
Ksi:	$0.012\ s^{-1}$	Kpi:	$0.055\ m \cdot MPa^{-1} \cdot s^{-1}$

Simulation results are validated in actual tests in the VTI T-38 wind tunnel. Comparison of simulation and experimental results for the tank pressure, the blowing pressure and the valve position at Mach 2 and Mach 4 is given in Figure 14.

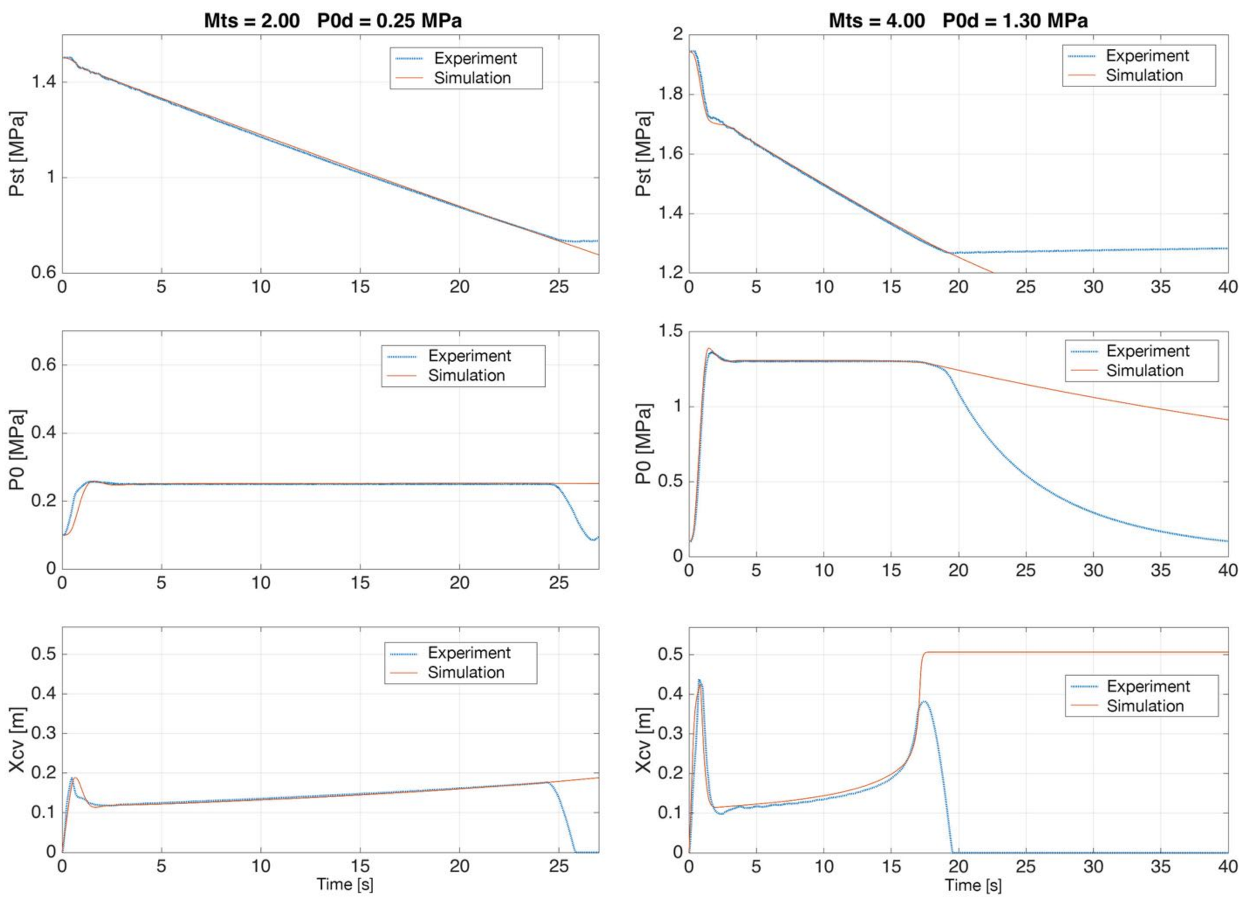

Figure 14 – Simulation and experimental results at Mach 2 and Mach 4

Agreement between simulation and experimental results for blowing pressure in the entire range of the VTI T-38 test facility is within 1%. Initial valve position is up to 5% higher in experiments than in simulations due to difference between the plenum volume (V_0 = 360 m^3) used in the model (1) – (9) and the effective plenum volume that is somewhat different and changes for different nozzle configurations. In reality, the effective plenum volume also accounts for the convergent part of the nozzle before the throat and it is certainly larger than the geometrical volume, bringing somewhat higher mass flow losses during the plenum filling period, which explains higher initial valve openings in the actual wind tunnel tests.

However, these differences are relatively small and consistent to justify additional calculations. Based on comparison of simulation and experimental results, the flow dynamics model (1) – (9) and the controller model in Figure 13 proved themselves reliable tools for design and tuning of the blowing pressure controller in the VTI T-38 wind tunnel. Although these tools are applied specifically to the VTI T-38 wind tunnel, they are designed to be general enough to represent a control framework for any blowdown test facility and a method to improve performance of these facilities.

In Figure 15, blowing pressure control in the VTI T-38 wind tunnel is demonstrated for the entire supersonic range of the facility, from Mach 1.5 to Mach 4, for setpoint pressures from 0.25 MPa to 1.35 MPa. The blowing pressure curves represent data sampled with the rate of 250 Hz, each sample containing the first 5 seconds of 14 wind tunnel tests done for different blowing pressure and Mach number combinations.

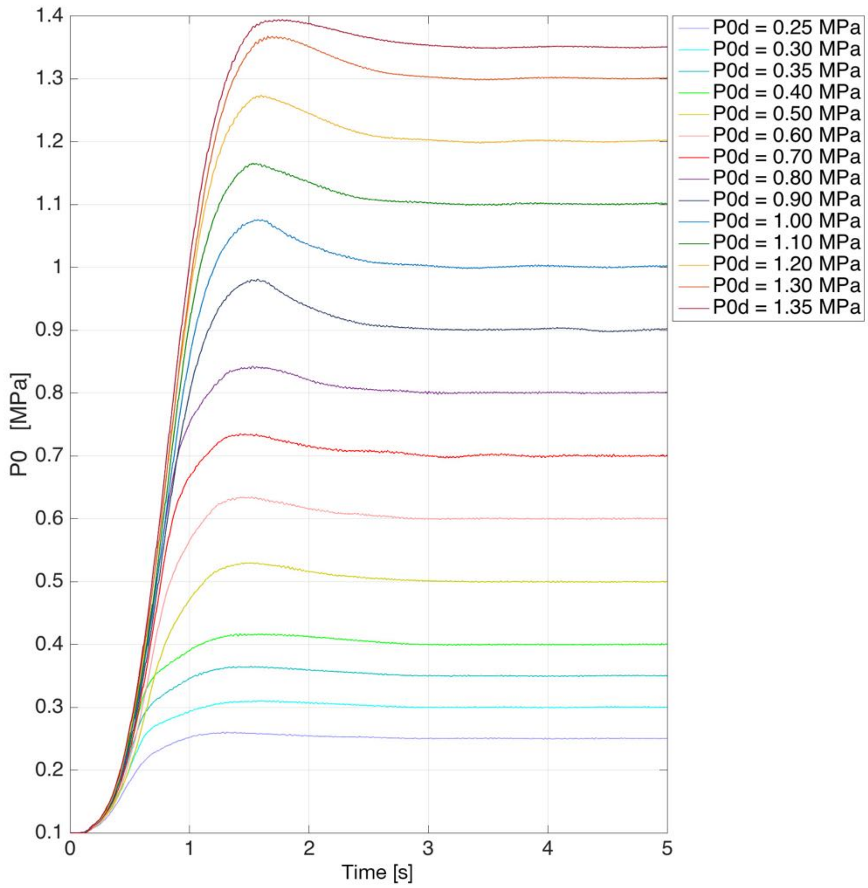

Figure 15 – Blowing pressure control in the supersonic range of the VTI T-38 test facility

3.8 Setpoint tracking performance

The first of the two main objectives of the control strategy implemented in the VTI T-38 wind tunnel was to achieve good setpoint tracking performance. The primary feedback controller with feedforward action was intended to achieve as accurate as possible setpoint tracking by compensating both measured and estimated sources of nonlinearities.

The blowing pressure setpoint tracking is analyzed in the steady-state conditions, in intervals lasting 10 seconds, from 5th to 15th second of the wind tunnel tests done in the supersonic operating range. The zoom-in plots of the blowing pressure in relation to the setpoint are given in Figure 16 for wind tunnel tests at M_{TS} = 2 and P_{0d} = 0.25 MPa and M_{TS} = 4 and P_{0d} = 1.3 MPa.

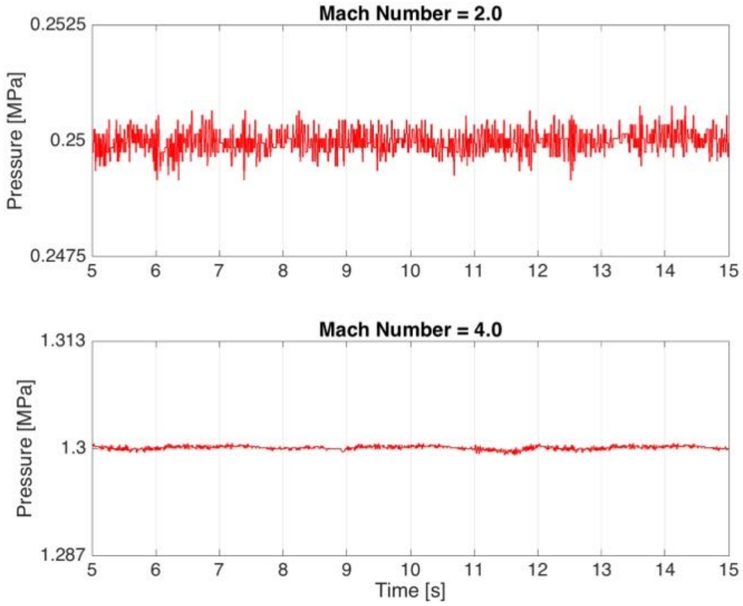

Figure 16 – Blowing pressure control samples

Statistical analysis of the blowing pressure samples indicated good agreement with setpoint values [21]. Absolute differences between the mean and setpoint values increase with pressure, but expressed as percentages of the setpoints, these differences range from 0.020% at Mach 2 to 0.016% at Mach 4. Average absolute deviations from mean values are 0.078% at Mach 2 and 0.029% at Mach 4. Standard deviations from the setpoint are 0.099% at Mach 2 and 0.036% at Mach 4. In general, the controller implemented in the VTI T-38 wind tunnel achieves blowing pressure control uncertainty of ±0.1% of the setpoint in the entire supersonic range, which represents a noticeable improvement in comparison to the common single-loop solutions [16] [17] stating control accuracy of ±1%. The accuracy of ±0.1% is also indicated in some case-by-case control solutions [19] [26], but at the cost of higher complexity of the controllers and complicated adjusting procedure.

The performance of the blowing pressure control strategy implemented in the VTI T-38 wind tunnel certainly meets the criteria set by ever more stringent requirements for measurement quality. To the best of the authors' knowledge, blowing pressure control accuracy of ±0.1% is the highest that has been reported so far in blowdown wind tunnels. However, the equally important result from the perspective of reliability and economy of wind tunnel operations represents development of formal control methodology applicable to any blowdown test facility. System integration time and cost are significantly reduced by analyzing physical properties of the process in the early stages of the system development. By identifying and modelling main sources of nonlinearities, tuning activities are carried out almost entirely in the simulation phase. Then the expensive wind tunnel tests are mostly done to confirm simulation results, minimizing the cost of system integration and validation.

3.9 Disturbance rejection performance

The second of the two main objectives of the control strategy implemented in the VTI T-38 wind tunnel was to achieve good disturbance rejection performance. The secondary feedback controller was intended to improve disturbance rejection in order to minimize both the blowing pressure transient overshoot and settling time.

The problem of blowing pressure transient overshoot is common in blowdown test facilities, and different techniques have been used to decrease the settling time with mixed results [23] [24]. Some of these techniques involve high pressure overshoot in order to achieve shorter settling time, thus bringing also high aerodynamic loads acting on the tested model. However, due to transient pressure oscillations, this approach cannot be expected to result in improved settling time in the entire operating range of the facility.

In contrast, the cascade architecture implemented in the VTI T-38 wind tunnel brings decreased settling time with pressure overshoot of up to 6% of the setpoint (Figure 15) as a result of fast response and aggressive tuning of the secondary controller. The feedback action of the controller is dominant at the beginning of a test in comparison to feedforward action, which is dominant after the flow is established. In Figure 17, feedforward contribution to the valve position is given for tests at Mach 1.5, Mach 1.75 and Mach 3.

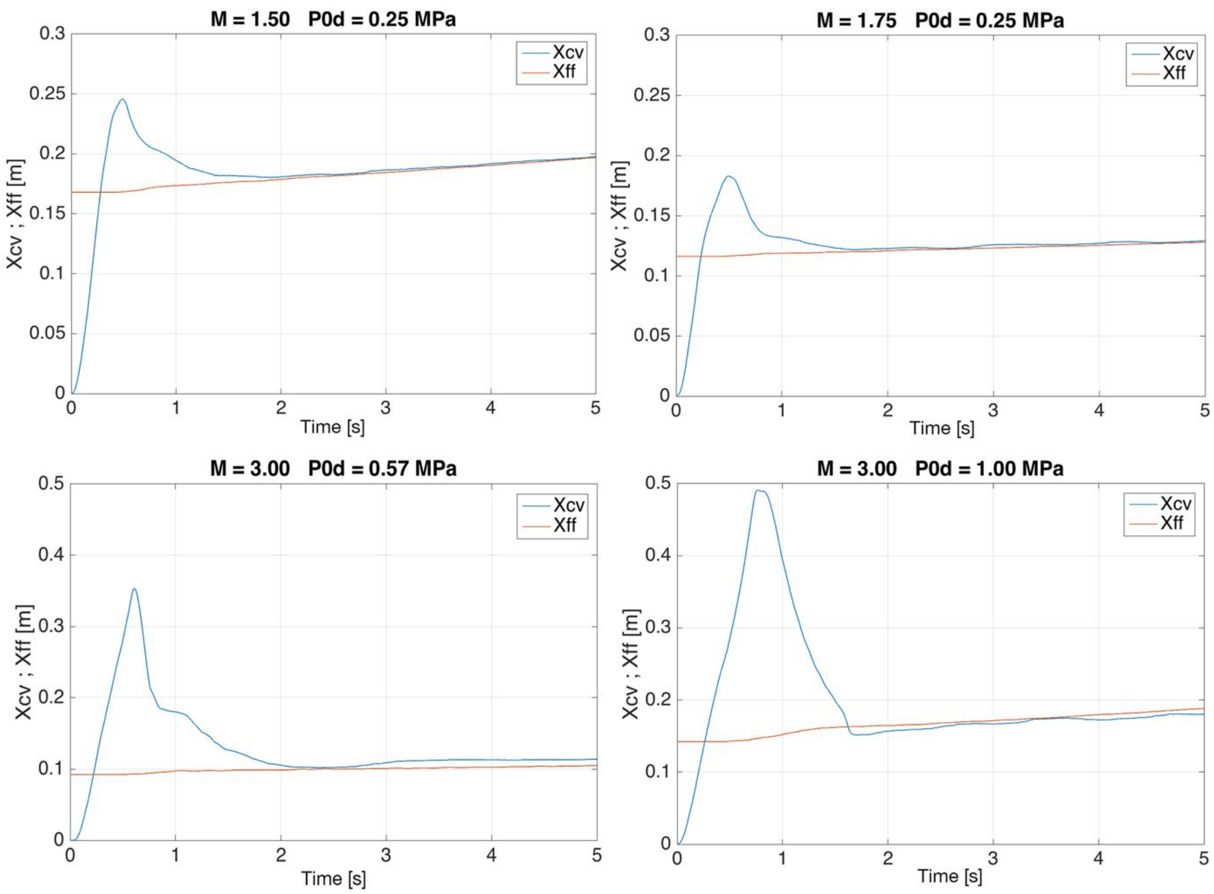

Figure 17 – Feedforward contribution to the valve position

In all test conditions, the feedback output is significant at the beginning of the test, contributing to the fast plenum filling notwithstanding large required blowing pressure differences. For example, two tests at Mach 3 in Figure 17 are done at different blowing pressures, 0.57 MPa (lower left) and 1 MPa (lower right). Initial valve opening is higher in the second case due to the feedback action responding to the higher pressure needed in the plenum. In both cases, the blowing pressure settling time is 2.8 seconds. In Figure 15, it can be noticed that the blowing pressure settling time is less than 3 seconds in the entire supersonic range of the VTI T-38 wind tunnel, which is in line with expectations based on the plenum volume, the valve characteristics and maximum mass flows at different Mach numbers.

As expected, the feedforward action dominates in the steady-state phase of the tests, when the flow is established. The feedback output is close to zero in this phase, confirming that compensation algorithm is effective and accurate in capturing nonlinearities in the facility response.

3.10 Comparison before and after

The blowing pressure controller implemented within the novel VTI T-38 wind tunnel automation platform has brought significant improvements in both setpoint tracking and disturbance rejection performance in comparison to the previous wind tunnel control system.

Comparison of the setpoint tracking performance before and after the VTI T-38 wind tunnel upgrade is presented in Figure 18. The blowing pressure data sampled in intervals lasting 15 seconds in wind tunnel tests at two very different sets of conditions, M_{TS} = 1.5 and P_{0d} = 0.25 MPa and M_{TS} = 3 and P_{0d} = 1 MPa, are compared between the previous and current control system.

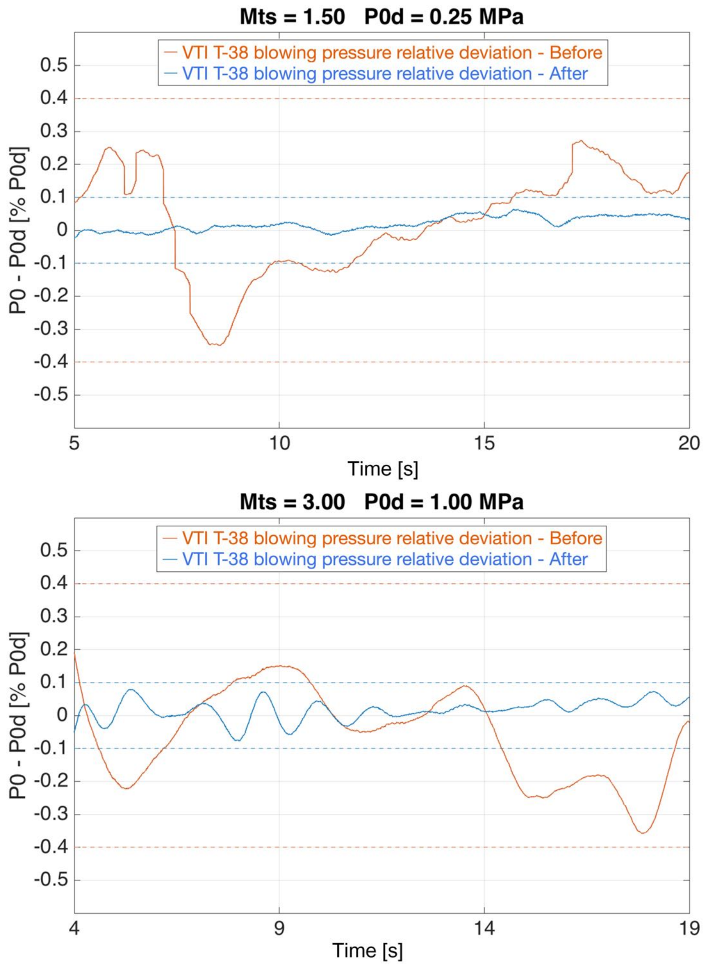

Figure 18 – Blowing pressure relative deviations from the setpoint - before and after

For both Mach numbers and for both setpoint blowing pressures, the control uncertainty of the current controller is better than ±0.1% of the setpoint, in comparison to the relative deviation from the setpoint of ±0.4% obtained with the previous system. The effect of several times better blowing pressure control uncertainty on the measurement accuracy is not negligible, since it propagates to all parameters measured on the models in wind tunnel tests. This effect is yet to be estimated.

Comparison of the disturbance rejection performance before and after the VTI T-38 wind tunnel upgrade is presented in Figure 19. The blowing pressure data sampled in the first 8 seconds of wind tunnel tests at two different sets of conditions, M_{TS} = 1.5 and P_{0d} = 0.25 MPa and M_{TS} = 3 and P_{0d} = 1 MPa, are compared between the previous and current control system.

The settling time of the current controller is less than 3 seconds in both wind tunnel tests, in comparison to settling time of 5 - 7 seconds typical for the previous control system.

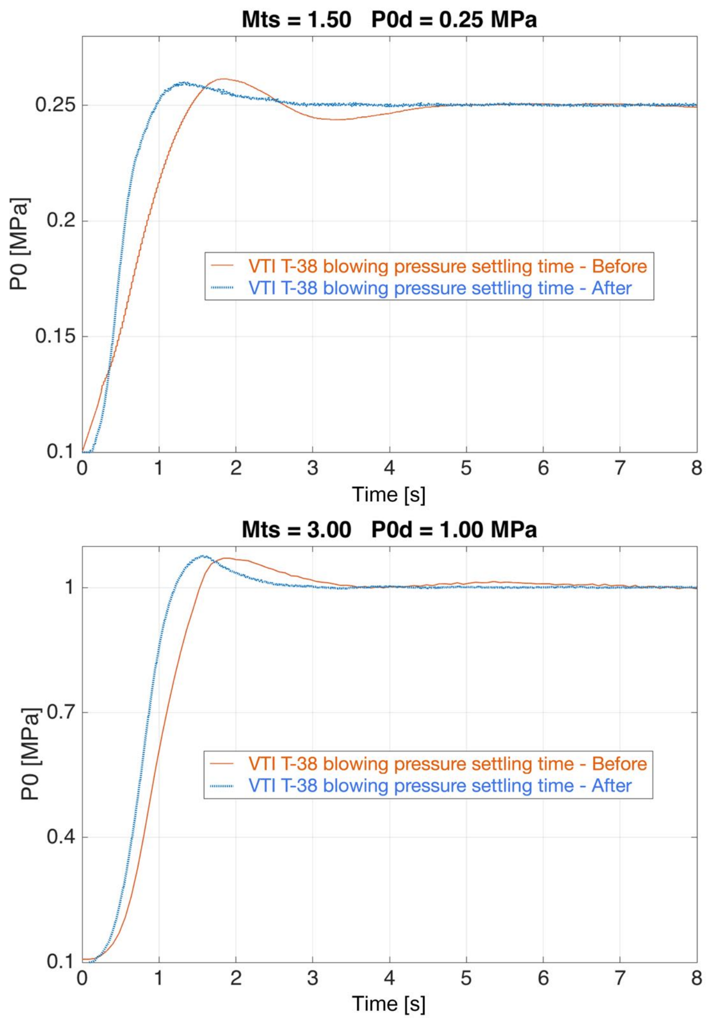

Figure 19 – Blowing pressure settling time - before and after

The technique applied in the previous system for transitional blowing pressure control was based on minimizing overshoot in order to decrease high starting aerodynamic loads acting on the tested model, but at the cost of longer blowing pressure settling times. In addition, at high supersonic Mach numbers (≥ 3) in the VTI T-38 wind tunnel, the residual blowing pressure low-frequency oscillation was present for the duration of a test [10]. Decoupling between the flow and the valve dynamics in the current solution enabled the aggressive tuning of the secondary (valve) controller and fast disturbance rejection, which results in better transient control of the blowing pressure with similar overshoots as before, but with much shorter settling times.

Several seconds shorter blowing pressure settling times with the current controller bring several seconds longer available test times (Phase II in Figure 7) for the same initial tank pressure. It is also important from the energy saving perspective. For reference, an estimated energy saving potential of 2 seconds shorter settling time during a typical working day is at least 20%, or at least 4800 kWh daily in absolute terms for the VTI T-38 test facility.

4. Summary

An overview of the novel solution developed by VTI for automation of aerodynamic experiments in the VTI T-38 test facility is presented in this paper, with special insight on the wind tunnel control system as an essential part of the developed automation platform. The unique features of the VTI T-38 wind tunnel control system, namely separation of facility and test functions, and at the same time their complete integration, are demonstrated using the case of blowing pressure as the primary flow parameter in blowdown wind tunnels.

The blowing pressure control strategy in the VTI T-38 wind tunnel is designed in several steps presented in the paper:

- The nonlinear dynamic model of the wind tunnel flow is developed, which is applicable to subsonic, transonic and supersonic speed regimes. Since the model captures only flow dynamics common to all blowdown facilities, without taking into consideration internal dynamics of the control element, it can be generalized and used to analyze the response of any blowdown wind tunnel and identify nonlinearities originating from flow dynamics separately from the control element nonlinearities.
- The process physical properties are analyzed and distinct contributions to the overall process gain originating from flow dynamics and valve internal dynamics are identified.
- With clearly identified contributions of flow dynamics and valve properties in the process gain, a cascade control architecture is proposed, reflecting decoupling between the slower flow dynamics and the faster valve dynamics. A double-loop scheme enabled separation of test and facility functions. Due to highly nonlinear flow dynamics represented by the model of wind tunnel flow, feedforward with feedback trim architecture is selected for the slower loop.
- Feedforward action is designed to compensate for the most prominent sources of nonlinearities, both measured ones (such as the tank pressure) and the estimated ones (such as settling chamber pressure losses). Remaining disturbances are intended to be counteracted by feedback action.
- The feedback control terms of the cascade controller are tuned in numerical simulations using the model of the process. A single set of feedback control terms is identified as appropriate for all operating conditions.
- The suggested strategy for blowing pressure control is implemented within the VTI T-38 wind tunnel automation system. Wind tunnel tests confirmed that selected control strategy resulted in a robust controller with a single set of feedback control terms and uniform performance in the entire operating range of the test facility.

An analysis of blowing pressure control performance pointed out to several important technical features delivered by the VTI T-38 automation platform in overall:

- Complete vertical integration.
- True separation of test and facility functions.
- Improved accuracy, determinism and reliability.
- Minimized tuning efforts.
- System integration cost savings.
- Facility operation cost savings.

While this paper focuses on the blowing pressure control as a reference case, the same principles have been successfully applied to the control of other test parameters within the wind tunnel control system, thus bringing further improvements in the operation of the VTI T-38 test facility.

5. Contact Author Email Address

mailto: biljana.ilic@icloud.com, biljana.ilic@vti.vs.rs

6. Copyright Statement

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